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Cherenkov x Rays: Recent Experimental Results

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Preliminary experimental results show the measurement of Cherenkov x rays for silicon and carbon foils. The measured distributions demonstrate grazing-angle enhancement of the emission flux, where relativistic electrons are incident on the foils at near-grazing angles. This behavior was predicted in a paper presented at the preceding Werner Brandt Workshop.

I. INTRODUCTION

A talk presented at the previous Werner Brandt Workshop reviewed the physics of x-ray generation by the Cherenkov effect and used ideal theoretical calculations to predict that grazing incidence of relativistic electrons on thin foils could be used to dramatically increase the photon fluxes produced by Cherenkov x-ray sources.[1] Previous experimental and theoretical reports in the literature had discussed the basic nature of x-ray Cherenkov radiation (CR),[2] but the possibility of using grazing incidence to enhance x-ray CR had not been considered or discussed previously. This paper presents preliminary experimental results that confirm our prediction of grazing-angle enhancement of CR from thin foils of silicon and carbon.

This work has been pursued because a variety of theoretical calculations had suggested that Cherenkov x rays could be available throughout the x-ray spectral region; but experimental results had proven difficult to obtain.[1,2] The present authors had failed to detect Cherenkov x rays in two preliminary experiments that used perpendicular incidence of electrons on thin foils of Be, C, and Ti. The theoretical predictions had depended on highly uncertain estimates of the anomalous dispersion of dielectric constants near atomic resonances in the optical medium of interest. After the negative experimental results, a series of calculations was performed to predict more exactly the expected emission distributions and to determine whether some new technique, such as grazing electron incidence, might enhance the radiated Cherenkov emission intensity.

These calculations were described in the previous paper.[1] The calculations used published values[3] of anomalous refractive indices in crystalline silicon near the L-edge resonance ($\approx$ 100 eV) together with exact theoretical descriptions of radiation generated by electrons incident in thin foils with arbitrary angles of incidence.[4,5] The calculations verified that simple approximate formulas correctly predicted the CR emission intensity for perpendicular incidence. The calculations also predicted that the CR intensity could increase by as much as two decades if the electrons were incident on the thin foils with near-grazing angles of incidence. Although the absolute CR flux depended on the values used for the anomalous refractive indices, the grazing-angle enhancement was found to occur whenever the refractive index exceeded unity.

II. THEORY

The basic theory of CR has been discussed in our previous report. For the present purposes it is useful to write a simple equation that describes the number of photons, N_f, generated with normal incidence of an electron on a thin dielectric foil:[6]

$$N_f \approx 4\pi^2\alpha\left(\frac{l}{\lambda_0}\right)\left(\frac{\Delta\omega}{\omega}\right)\chi' \,. \tag{1}$$

where $\alpha \approx 1/137$, l is the foil thickness, λ_0 is the vacuum wavelength of a photon with radial frequency ω. χ is the complex dielectric susceptibility: $\chi = \chi' + \chi''$, and $\Delta\omega$ is the bandwidth over which a single value χ' describes the dielectric constant at ω.

Recall that the dielectric constant $\varepsilon(\omega)$ is given by: $\varepsilon(\omega) = 1 + \chi$ and that the refractive index, $n(\omega)$, becomes: $n(\omega) = \sqrt{\varepsilon(\omega)} \approx 1 + \chi'/2$. The electron must have γ (total energy divided by electron rest mass) greater than the threshold value : $1/\gamma_{th} \approx \sqrt{\chi'(\omega)}$. When $\gamma >> \gamma_{th}$ the CR will be emitted into a cone with a half angle θ_{cr} given by:

$$\theta_{cr} \approx \sqrt{\chi'(\omega)}\,. \qquad (2)$$

II. EXPERIMENT

An experiment has been performed to investigate grazing-angle enhancement of x-ray CR. Figure 1 shows a schematic diagram of the experimental arrangement. 75-MeV electrons produced by the LLNL electron-positron linac were directed at thin target foils and then were deflected by a "dunp" magnet to a scintillation beam-current monitor in a beam dump hole. The scintillation monitor was calibrated by comparison with a "beam block"/electrometer measurement of the absolute current. The target foils could be rotated about an axis perpendicular to the electron trajectory, allowing variation of the electron angle of incidence on the foil from perpendicular to near grazing angles. The angular distribution of radiated photons was measured by moving a proportional counter along an axis that intercected the electron direction and also was perpendicular to the axis of rotation of the target. The samples were a 2.5 cm by 7.5 cm by 500 $\mu g/cm^2$-thick vapor-deposited carbon membrane from Arizona Carbon Foil Co., Inc., and a 2.5 cm-square x

3μm-thick single crystal silicon membrane that was removed from a wafer supplied by Nanostructures, Inc..

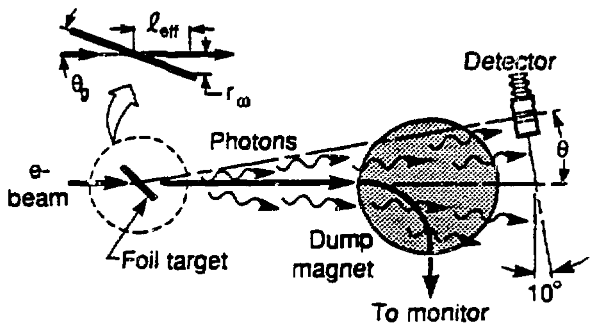

Figure 1 Schematic Diagram of Experimental Setup

Typical average electron beam currents were about 1 pico (10^{-12}) A. Even at these current levels, the proportional counter sometimes experienced photon pileup problems that tended to "compress" the amplitude of angular features and reduce the measured peak intensities. In addition, residual fluorescence in the scintillation monitor, noise in the electrometer, and uncertainty in the detector sensitivity for low photon energies restricted the absolute overall system calibration to be no better than a factor of four.

III. RESULTS

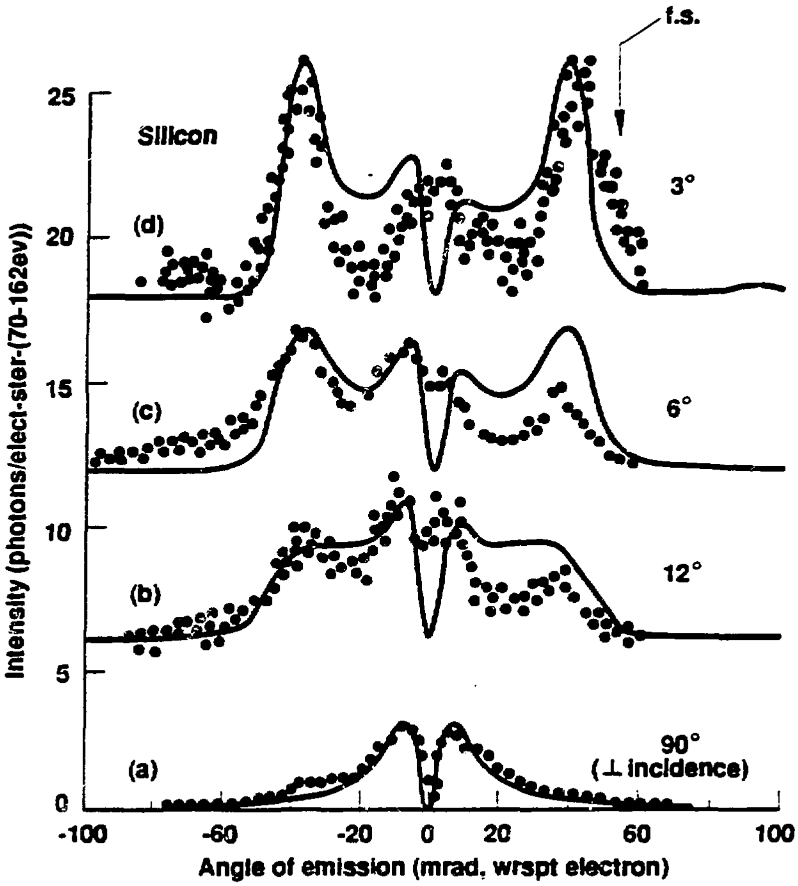

Figure 2 Measured (dots) and calculated (solid) angular distributions for the silicon sample. Figures (a) through (d) show the data for angles of incidence from 90° through 3°, respectively. F.S. indicates the foil surface direction for small grazing angle.

Figure 2 shows the angular distribution of photons measured (dots) for four different angles of incidence with the silicon target. A single-channel analyzer restricted the recorded pulses to correspond to a photon-energy window of 70-162 eV. The figure also shows calculations (solid) based on exact solutions of radiation generated when relativistic electron penetrate thin dielectric foils with arbitrary angles of incidence. The absolute intensity of the data are normalized to the theoretical calculations, because analysis of the absolute intensity of the measured data is not yet complete.

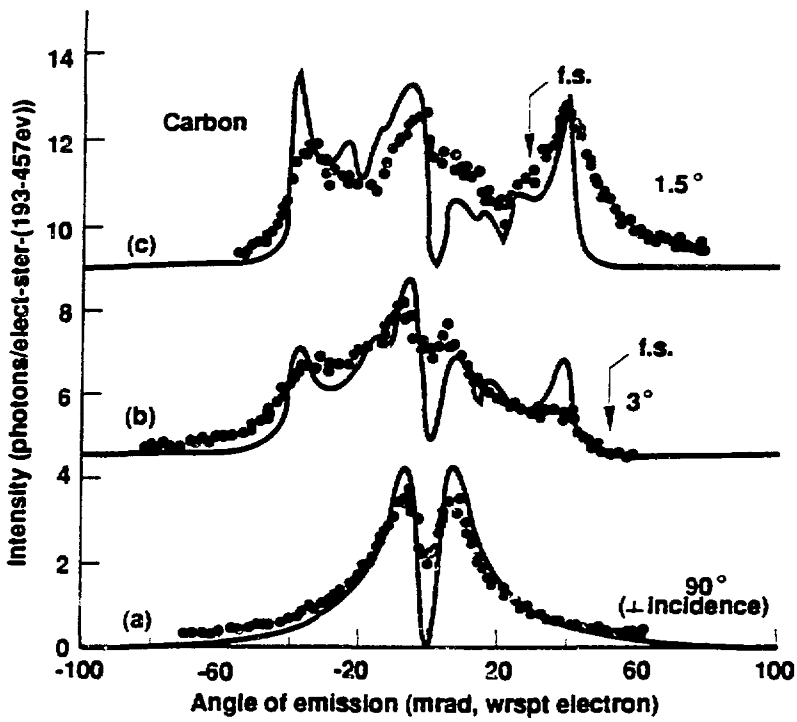

Figure 3 Measured (dots) and calculated (solid) angular distributions for the carbon sample. Figures (a) through (c) show the data for angles of incidence from 90° through 1.5°, respectively. F.S. indicates the foil surface direction for small grazing angle.

Figure 3 shows similar data for the carbon foil with three different angles of incidence. In this case the photon energy window was set to 193-457 eV. Again, the absolute intensity of the data are normalized to the theoretical calculations.

IV. DISCUSSION

The data in Figs. 2 and 3 show angular distributions that change dramatically with the electron angle of incidence on the foils. For perpendicular incidence (Figs. 2(a) and 3(a)) the distributions are similar to those normally expected from transition radiation (TR): they show an on-axis minimum and have peaks at angles of about $\approx 1/\gamma$ ($1/\gamma \approx$ 7 mrad). As the foils are tilted to smaller grazing angles of incidence the data begin to show extra peaks at angles of about ± 40 mrad. As the grazing angles are decreased these extra peaks become stronger. In the silicon sample the "extra" peaks increase until, with a 3° grazing angle, they dominate the angular distribution. Note that the Cherenkov peaks represent spectral fluxes roughly 2 decades greater than for the TR (since the TR was detected in a large energy "window", and the CR is inherently narrow).

The data in Figs. 2 and 3 give strong evidence for x-ray Cherenkov emission that is enhanced by the grazing-incidence geometry. The peaks at ±40 mrad are at an angle that is much too large to be associated with most other relativistic radiation processes. Processes such as bremsstrahlung or channeling radiation have on-axis peaks with angular FWHM of about $2/\gamma$, and TR has an on-axis minimum with peaks at ± $1/\gamma$. The Cherenkov effect is the only mechanism that gives a simple explanation for the observed behavior. Equation (2) can be used to interpret the observed Cherenkov angle in terms of the associated susceptibility $\chi'(\omega)$. The 40-mrad angle implies $\chi' \approx 0.0016$. This value is not inconsistent with recently measured values for carbon near 280 eV,[7] but is much smaller than published values for the anomalous χ' for silicon at 100 eV.[5]

The calculations shown in Figs. 2 and 3 are based on the same theories that were used previously, but they have been modified to account for effects such as refraction and reflection at dielectric boundaries. The calculations for silicon use $\chi' \approx 0.0016$ near 100 eV, and $1-\omega_p^2/\omega^2$ away from the resonance. If the calculations use the published values for χ' near 100 eV then the x-ray CR is strong at angles as large as 15° and does not resemble the measured data.

V. CONCLUSIONS

The data above gives strong evidence for grazing-angle enhancement of x-ray CR. The experiment was motivated by theoretical calculations of expected emission distributions. The calculations predicted the grazing-angle enhancement behavior that we seem to have observed, but a number of other features such as absolute intensity, angular symmetry and angles of emission presently do not agree with the data. Currently, we are in the process of reviewing the data in an attempt to resolve some of these discrepancies and in order to be able to draw some definite conclusions from the results. Difficulties of this type are not unusual in a nedw experiment and we believe that the qualitative features of the data give strong evidence for grazing-enhanced x-ray

CR. If this is correct, then this process will prove to be useful for characterizing anomalous $\chi'(\omega)$ near atomic resonances. Finally, since the CR is intense and spatially coherent, it may lead to the design of new efficient coherent x-ray sources.

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